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Reliability Improvement of Vibration Energy Harvester with Shock Absorbing Structures

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Abstract

In this article, we described concepts for improving the shock reliability of MEMS electrostatic vibration energy harvesters. The harvester is based on silicon mass spring system supporting an electret. We determined experimentally that the primary cause of failure of the harvester under shock excitation is impact between the anchors of the springs. The impact creates chipping damages on the anchors which induces breakage of the springs. The springs are vital for proper functioning of the harvester, so that when they are broken, the device losses all its functionalities. Avoiding impact between moving parts of the harvester is difficultly feasible. However, avoiding impact on vital parts of the device is easily feasible with the use of shock absorbing bumpers. The concept of rigid bumpers is first investigated. While this approach improves the survival chances of the springs under a shock excitation, chipping damages are observed on the rigid bumpers. The residue from the chipping damages may hinder the functionality of the harvester. To limit the chances of chipping damages on the bumpers, flexible in place from rigid bumpers are investigated. By using Hertz contact model approach, it is shown that flexible bumpers allow reducing the risk of chipping damages by a factor five.

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Keywords: Energy harvester, electret, vibration, shock reliability, flexible bumper

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1. Introduction

The harvester discussed in this article has been successfully integrated into an autonomous wireless tire pressure monitoring system (TPMS) [1]. The device consists of a $10 \times 10 \times 0.65$ mm^3 silicon proof mass supporting a corrugated electret. The electret faces slit shaped counter electrodes. The mass is supported by four single-folded springs, which create a mechanical resonator with a resonance frequency of about 1.1 kHz. In a tire environment, the device shows a power generation of 15 µW at 50 km/h driving velocity, which has been shown to be sufficient to power for the TPMS [1]. To bring the product closer to the market, the harvester should meet stringent requirements in terms of shock resilience. Our objective is to make harvesters that survive half sine shocks with amplitude of 2500 g and duration of 0.6 ms. This would be within safety margins of the standard requirements of the automotive industry [2].

In this study, we first present the failure analysis in shock environment of the mechanical resonator in our harvesters. It is shown that failure of the device is related to impact between moving parts of the harvester vital for its proper functioning. Also, the goal of 2500 g shock survival is far to be reached with our first generation devices. Therefore, concepts for improving the shock reliability of the MEMS harvesters are described. Rigid shock absorbing structures (bumpers) are first investigated. It is shown experimentally that this approach allows improving the reliability of the devices. However, chipping damages are observed on the bumpers. The chipping residue may induce short circuit on the electrodes of the device or may hinder the motion of the mass. Therefore, they should be avoided. To limit the risk of chipping damages on the shock absorbing structures, the concept of flexible bumpers is investigated. By using a model based on Hertz contact theory, it is shown that the flexible bumpers dramatically reducing the risks of chipping damages.

2. Failure mechanism on drop test

The first step to improve the reliability of the devices is to understand how they break. The design of the mass spring system in the first-generation harvester is described in Fig. 1 (a). The springs on both sides of the mass are connected together by a truss and the silicon mass of 151 mg can travel in a ±100 µm range. Since mechanical failure of the harvesters in shock environments occurs within parts of the mass-spring resonator, the shock test was done on dummies consisting solely of the resonator part. As shown in Fig. 1 (b), the Si mechanical resonator is glued on 2 mm thick FR-4 board and attached to the drop mass of the drop tester (Shock Test System Model 23; Lansmont Corporation, USA).

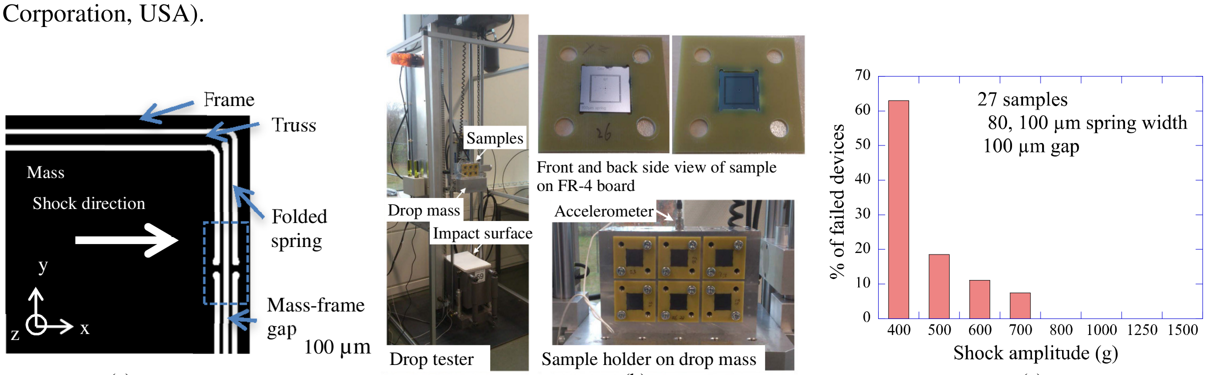


Fig. 1. (a) One-fourth schematic of the first generation electrostatic harvester; (b) Drop tester equipment; (c) Statistical result of the shock resilience measurement on 100 µm mass-frame gap and 80, 100 µm spring width for the 27 tested samples.

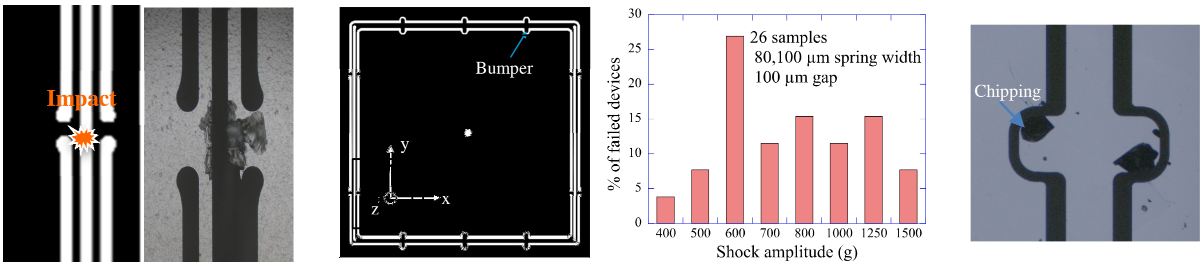
A series of half-sine shocks with 0.6 ms duration and increasing amplitude was applied to a population of samples. Shocks were applied in different directions and it was determined that the x direction was the most problematic. The results of the experiments in terms of shock survival for x-directed shocks are reported in Fig. 1 (c). Most of the devices are broken for shock amplitude around 400 g. The automotive industry shock resilience requirements are then far to be met and the reliability of the devices should be improved. A picture of a device broken after a shock test is given in Fig. 2 (a). Chipping damages are present at the location where moving parts of the silicon resonator comes into contact during a shock. All the tested samples were broken in the same manner. The process of impact between the anchors of the springs and the resulting chipping damages is then strongly suspected to be the cause of failure of the devices. In contrast to highly shock reliable MEMS devices [4], we cannot decrease the mass or the range of motion to limit chipping damages, as it would also mean declining the generated power. Another option is to redirect the impact to parts of the mechanical resonator that are not critical for its proper functioning by making use of bumpers.

3. Rigid bumper

To redirect the impact on non-vital parts of the structure, i.e. far away from the spring anchors, bumpers are introduced in the design, as illustrated in Fig. 2 (b). To prevent collisions on the spring anchors, the gap between the anchors of the springs is extended to 105 µm while the bumper-mass and bumper-frame gaps are set to 50 µm. Since the displacement of the bumpers attached to the truss is half that of the mass, there is still a 5 µm gap between the anchors of the spring when the bumpers collides with either the frame or the proof mass.

The same test procedure than that discussed in section 2 was applied to the devices with rigid bumpers. The results in terms of shock survival rate are given in Fig. 2 (c). It can be seen that the shock resilience is in average better than for devices without bumpers. However, in some cases, the bumpers are completely fractured during the collision. In this case, they neither allow limiting the motion of the mass nor avoiding impact between the spring anchors. Also, when the bumpers are not completely fractured during impact, chipping damages are observed on their surface (Fig. 2d). The residue of the chipping damages may be harmful for the proper functioning of an assembled harvester (short circuit on the electrodes, hindering of the mass motion).

In order to reduce the risk of fracture or chipping residues on the bumpers, one should reduce the contact force between the bumpers at impact. To this aim, flexible bumpers are investigated in the next section.



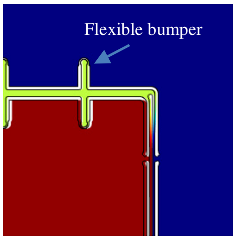
(a) (b) (c) (d)

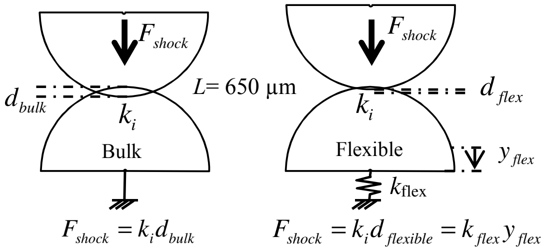
Fig. 2. (a) Picture of the typical failure found around the spring anchor (dashed line rectangular area in Fig. 1a). Chipping damages are present on the contact edge and spring is broken; (b) Schematic drawing of the harvester with the rigid bumper on the truss. The mass and the frame have no collision by the limitation of the rigid bumper on the truss; (c) Statistical result of the shock resilience measurement with rigid bumper for the 27 tested samples; (d) Picture of the typical failure on the bumper.

4. Flexible bumper model

The proposed concept of flexible bumpers is illustrated in Fig. 3 (a). It can be understood that, under a shock, the flexible bumpers will undergo bending deformations. Our primary goal is to avoid contact between the anchors of the springs, so that we have to make sure that the gap between the spring anchors is larger than the displacement of the flexible bumpers for the maximum amplitude of the applied shock, which is 2500 g in our case. With the help of FEM simulations, we designed flexible bumpers with two different stiffness of 1.5 MN/m and 430 kN/m. Under a 2500 g shock with 0.6 ms duration, the maximum expected displacements of the flexible bumpers are 25 and 50 µm, respectively. Note that the maximum bending stress occurring in the springs at maximum displacement will be larger in the devices with flexible bumpers than in the devices with rigid bumpers. It is however expected not to be an issue.

In order to quantify roughly the reduction of the risk of chipping damages between rigid and flexible bumpers, we hypothesized that this risk can be related to the indentation of the silicon during contact: the lower the silicon indentation, the lower the risk of chipping damages. An estimation of the reduction in indentation by using flexible bumpers in place of rigid ones can be obtained by considering the ideal situations of Fig. 3 (b). The contact surface between the bumpers can be approximated as a cylinder-cylinder Hertz contact problem [5]. In the Si bulk surface, the collision force is calculated by applied shock force, F_{shock} as shown in Fig. 3 (b). A material dependent bulk indentation stiffness, k_i also denotes in Fig. 3 (b), where E_{Si} is Young's modules of Si, 166 GPa, ν_{Si} is Poisson's ratio of Si, 0.27, and the L is thickness of the device, 650 µm.





$$k_i = \frac{\pi}{4} \frac{E_{Si}}{2(1-\nu_{Si}^2)} L$$

$$R_i = \frac{d_{bulk}}{d_{flex}} = \sqrt{1+\frac{k_i}{k_{flex}}}$$

(a) (b)

Fig. 3. (a) One-fourth FEM analysis model of the harvester with 1110 µm length flexible soft bumper; (b) Hertz contact ideal model of indentation for bulk and flexible bumper.

In the flexible bumper, two springs of bulk indention stiffness of k_i and flexible bumper spring constant of k_{flex} are connected in series. If the applying shock energy is converted completely to the indentation energy, the indention depth ratio can denote as R_i in Fig. 3 (b), which shows the softer bumper stiffness the lower indention depth. Same calculation result for rigid bumper model is also reported in Table 1. The chipping risk on the flexible soft bumper will be reduced to one-fifth from the rigid bumper model.

Table 1. Chipping risk comparison for rigid and two flexible bumper structures.

	Extra gap (µm)	Spring constant, k_{flex}	Bumper length /width (µm)	Chipping risk (%)
Second generation (Rigid)	5	14 MN/m	120 / 300	100
Third generation (Flexible, hard)	25	1.5 MN/m	605 / 200	37
Third generation (Flexible, soft)	50	430 kN/m	1110 / 200	20

5. Conclusion

In this study, the failure of MEMS electrostatic vibration energy harvesters under shock excitation is investigated. A campaign of shock test is first performed to determine the shock resilience of the harvesters. It is found that most devices break for a shock amplitude of 400 g which is not a satisfactory result. It is determined that the failure of the devices is related to the collision between moving parts of the harvester vital for its proper functioning, i.e. between the anchors of the spring. To improve the shock resilience, shock absorbing bumpers are introduced in the design. Rigid bumpers are shown to improve the shock resilience. However, chipping damages on the bumpers are problematic. To remediate this issue, the concept of flexible bumpers is investigated. From theoretical computations, it is determined that flexible in place of rigid bumpers allows reducing the risk of chipping damages by five.

Acknowledgements

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